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A REVIEW OF ISSUES AND
STRATEGIES IN NONDESTRUCTIVE
EVALUATION OF FIBER REINFORCED
STRUCTURAL COMPOSITES

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A REVIEW OF ISSUES AND STRATEGIES IN NONDESTRUCTIVE EVALUATION OF FIBER REINFORCED STRUCTURAL COMPOSITES

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Abstract

This paper emphasizes the need for advanced nondestructive evaluation (NDE) techniques for quantitative assessment of the mechanical strength and integrity of fiber composites during manufacture and service and following repair operations. Problems and approaches are discussed relative to acceptance criteria, calibration standards, and methods for NDE of composites in strength-critical applications. It is indicated that acousto-ultrasonic techniques provide the "methods of choice" in this area.

1. INTRODUCTION

This paper pertains to nondestructive evaluation (NDE) of fiber reinforced polymer and metal matrix composites that are beginning to replace metals in structures where high strength-to-weight ratios are important. These composites are usually in the form of laminates that are subject to variations in mechanical strength and integrity. NDE technology has a prominent role in assuring material quality and serviceability of composite structures (1)*. Key issues and strategies are reviewed relative to putting the NDE of composites on a quantitative basis.

*See references

2. NDE REQUIREMENTS

2.1 GENERAL REQUIREMENTS

Composites pose unique challenges to NDE because of their heterogeneous nature and susceptibility to fabrication errors, service damage, and environmental degradation. As a minimum, NDE techniques are needed to verify that the materials and workmanship used to produce a composite structure are uniform and high quality. There are specific requirements for NDE in five major areas:

- (1) Fabrication monitoring
- (2) Service certification
- (3) Damage assessment
- (4) Maintenance and repair
- (5) Development and testing

These requirements are discussed in sequence. It will be apparent from the following discussion that there is a need for NDE techniques to quantitatively characterize inherent materials properties as well as to detect and characterize discrete defects⁽²⁾.

2.2 FABRICATION MONITORING

Preliminary preparation stages for the fibers, matrix, and monolayers are monitored by various chemical and physical sampling tests. NDE methods are usually applied to composite laminates after the final cure cycle. At this stage, laminates or bonded structures require NDE for:

- (1) Degree of cure
- (2) Porosity and void content
- (3) Fiber/matrix ratio
- (4) Bond quality

These measurements require NDE techniques to confirm that the finished article meets specifications related to chemistry, microstructure, and physical and mechanical properties.

2.3 SERVICE CERTIFICATION

The service readiness of a laminate or composite structure is usually judged by NDE results that reveal fabrication errors and discrete flaws such as:

- (1) Interlaminar voids
- (2) Ply misalignments
- (3) Foreign inclusions
- (4) Fiber bunching
- (5) Matrix concentrations

- (6) Fiber and matrix cracks
- (7) Lack of bonding

Detection of the above imperfections is a necessary but not always sufficient cause for rejection. The relative importance of these flaws may depend on the way the part containing them is used. As discussed later under EFFECTS OF DEFECTS, some types of flaws are benign but advanced techniques may be needed for confirmation.

2.4 DAMAGE ASSESSMENT

Operating conditions and environmental effects can severely reduce the integrity and strength of composites. Damage can also occur during shipment and preparation for service. Damage and degradation mechanisms include:

- (1) Moisture penetration
- (2) Corrosion and chemical attack
- (3) Vibration and fatigue
- (4) Thermal cycling, overheating
- (5) Erosion and abrasion
- (6) Static overstressing
- (7) Impact and shock loading

While damage due to ballistic impact or exposure to fire is likely to be obvious, the extent of damage or effect on performance may be unclear. Degradation from chemical attack or fatigue with resin softening or microcrazing can be difficult to detect. These are examples of problems requiring advanced NDE methods.

2.5 MAINTENANCE AND REPAIR

In many applications, it may be

cost effective to repair or reclaim composite structures that have been damaged during shipment or service. NDE methods that are applicable under field conditions are required to determine:

- (1) Current integrity status
- (2) Severity of damage/degradation
- (3) Repairability
- (4) Repair integrity

NDE methods are needed to monitor the current condition of composite structures as a maintenance activity. If damage is found, NDE methods are needed to determine the degree of severity. Repairability may be confirmed by NDE methods. Advanced NDE techniques will be needed to verify the integrity and mechanical properties of the repair.

2.6 DEVELOPMENT AND TESTING

The development and testing of new composites is an ongoing process. NDE technology has an important role in the development and testing of new composite materials. NDE has three main functions in composites research:

- (1) Inspecting test specimens
- (2) Monitoring tests in progress
- (3) Analyzing test results

Fracture mechanics of composites are studied with the aid of NDE to monitor the growth of delaminations and cracks. Prior to testing, it is important to inspect experimental specimens for anomalies that would invalidate assumptions concerning the nature of the material

or its condition. Post test analysis can be improved by data available through NDE.

The verification of new design concepts and integrity of components is often accomplished by proof testing that incorporates NDE techniques for in situ monitoring of stress signatures. These testing and research applications require advanced NDE technology for quantitative characterization of material response to test loads.

3. NDE TECHNIQUES

3.1 CONVENTIONAL TECHNIQUES

The present state-of-the-art NDE techniques for composites will detect a variety of discrete flaws and structural imperfections⁽³⁾. NDE techniques commonly applied to composites include:

- (1) Ultrasonics (immersion and contact)
- (2) Radiography and radiometry (X-ray and neutron)
- (3) Visual-optical (including holographics)
- (4) Sonics (resonance and coin tap)
- (5) Penetrants (dye and radioactive liquids)
- (6) Dielectric (capacitance)
- (7) Electromagnetic waves (eddy current and microwaves)
- (8) Thermal (thermographic and thermochromic)
- (9) Acoustic emission (induced stress waves)

The most frequently used techniques

are visual, ultrasonic, sonic, and radiographic. Immersion and contact ultrasonic methods based on transmission of ultrasound through a material are widely used for revealing delaminations, matrix variations, porosity, and cracks. Radiography can reveal foreign inclusions and fiber misalignments while radiometry is a sensitive indicator of density variations. Visual examinations with or without optical aids are indispensable as a first order approach to finding surface-connected flaws. Dye and fluorescent penetrants are used to enhance the visibility of pores, cracks, and edge delaminations. Radio-opaque penetrants used in conjunction with radiography can help reveal the extent of surface-connected delaminations and voids. Coin tapping is widely used as an adjunct to simple visual examination to check for voids and disbonds hidden below surfaces. Sonic resonance can characterize bond integrity and in some cases relative bond strength. Holographic methods will show stress patterns that indicate near-surface flaws or material variations that affect vibrational modes. Dielectric methods are used for determining the degree of cure while eddy currents are used for sensing resin and void content. Thermal methods are used for finding voids and delaminations but like acoustic emission methods are most useful for monitoring flaw or damage propagation during frac-

ture and proof testing.

3.2 ADVANCED TECHNIQUES

As generally practiced, the previously described techniques yield only qualitative information concerning the inherent properties and service readiness of composite structures. In attempts to remedy this shortcoming, the development of advanced NDE technology is currently directed toward two major goals. These involve quantitative characterization of:

- (1) Discrete flaws or defects
- (2) Inherent composite properties

The first goal is concerned with augmentation of flaw detection with the capacity to characterize discrete flaws according to their nature, size, shape, location, and orientation. This leads to improved interpretations of the significance and potential effects of flaws.

The second goal is concerned with development of methods for characterizing various inherent material properties. In this case, the emphasis is on microstructure and morphological factors that determine mechanical properties. This leads to improved assessment of service reliability and residual life after exposure to service environments. Materials characterization also contributes to the prediction of the effects of flaws that may be present.

Some of the previously-listed NDE techniques have been adapted to the goals described above. Advances are

being implemented by combining NDE transducers and instrumentation with digital computers for improved:

- (1) Signal acquisition and analysis
- (2) Image generation & enhancement
- (3) Data storage and retrieval

Advanced instrumentation and high speed data processing and documentation concepts are being used to increase both the quantity and quality of information extracted by various NDE techniques (4).

However, as indicated in the following section, there are a number of basic problems that must be addressed before real progress can be made in the routine application of composites to strength-critical uses.

4. PROBLEM AREAS

4.1 EFFECTS OF DEFECTS

At present, there is a lack of clear understanding of the effects of defects in composites. Flaws or anomalies found by NDE techniques can often be ignored because they have no predictable adverse effect on strength or performance. Failure in service cannot be traced to known defects in many cases. Instead, the failure will appear to be controlled by subtle factors that are not revealed by commonly used NDE methods for finding overt defects (5).

The effects of defects are being studied relative to fracture mechanisms. In these studies, artificial defects are introduced in

test specimens. When tested to failure, these specimens will frequently exhibit failure modes that are unrelated to the introduced flaws (5,6).

In many instances, failure cannot be predicted from unintentional defects revealed by pretest NDE of test specimens. For example, it has been observed that even relatively large delaminations may be benign when they lie in planes parallel to load axes. And, unlike homogeneous brittle materials, many composites tend to be notch insensitive (6).

Apparently, the conditions that predispose composites to failure can consist of dispersed microstructural anomalies that constitute the environment of discrete detectable flaws. Although these individual flaws may be significant, the integrated defect state should be considered in assessing the viability of composites.

The above considerations point to a need for NDE techniques that are able to characterize inherent properties as well as discrete flaws, as mentioned previously under ADVANCED TECHNIQUES. The objective is to characterize the material morphological factors with which discrete defects will interact. However, practical application of the advanced NDE data will depend on having appropriate accept-reject criteria. Except in the case of gross overt defects, there are no standard accept-reject criteria for

composites. This leads to the problem of generating a fracture mechanics foundation for assessing the seriousness of various defects, as discussed next.

4.2 ACCEPTANCE CRITERIA

The establishment of accept-reject criteria ultimately depends on the identification of fracture mechanics parameters that control failure. At the initial stage, all failure mechanisms in composite laminates can be predicted and explained in terms of three fundamental modes ⁽⁷⁾:

- (1) Tensile, shear, or compressive failure of the matrix
- (2) Tensile or compressive failure of the fibers
- (3) Fiber/matrix interface failure

Once one of the above modes has been activated, subsequent stages will tend to involve interactions that defy theoretical prediction. Unlike isotropic materials, the fracture of anisotropic fiber-reinforced laminates is a multiparameter problem involving ⁽⁷⁾:

- (1) Constituent strengths & moduli
- (2) Lamination orientations
- (3) Flaw populations & distributions
- (4) Applied & residual stresses
- (5) Energy dissipation dynamics
- (6) Fracture propagation paths

Viewed realistically, the problem appears to be mathematically intractable due to the number of parameters involved. The interaction of these parameters is best studied experimentally.

NDE techniques can serve a dual role in the development of fracture models. First, NDE techniques can be (and are being) used in situ during fracture testing of composites to study flaw propagation patterns. Second, NDE techniques can be used to characterize various aspects of the specimen materials before and after destructive testing ⁽⁸⁾. These applications of NDE can greatly increase the understanding of the interaction of the six parameters listed above. The result should be improved failure mechanics models from which valid accept-reject criteria can be generated.

4.3 CALIBRATION STANDARDS

Progress in the assessment of the effects of defects and failure resistance of composites depends to a large degree on the availability of NDE techniques for precise material characterizations. The precision of the NDE techniques will require verification by means of appropriate calibration standards ⁽⁹⁾.

It is unlikely that a set of uniform universal standards can be created to cover the variety of conditions that arise in composite materials. But the standards should as a minimum provide consistent bases for resolving significant flaws and material variations in specific cases.

A current practice is to introduce artificial flaws having simple geometric shapes into composites. It is assumed that NDE measurements

of these implanted artifacts provide definitive calibration data. The degree to which this assumption is correct depends on the nature of the surrounding material. In laminates, there can be anomalous material variations that significantly modulate the NDE signals. For example, in ultrasonics the wave propagation effects in the material can strongly influence the signal returned from the "flaw." This problem arises even in homogeneous isotropic media. It should be recognized that the creation of composite NDE standards is difficult and, at present, an unresolved problem. It is also worth noting that advanced NDE methods will undoubtedly be needed to certify the quality and uniformity of any reference standards that are devised. This is an important consideration in the case of composites because slight variations in fabrication and processing can introduce significant fluctuations in material properties.

5. RECOMMENDED APPROACHES

5.1 CORRELATION CYCLE

A recurring theme in the preceding discussion has been the need for NDE techniques that quantitatively characterize intrinsic material properties. The emphasis is on nondestructive measurement of initial and residual strengths of actual articles prior to and in service. These measurements are indirect and depend on the existence of correlations among:

- (1) Material morphology
- (2) Mechanical strength
- (3) Modulation effects

Material morphology includes microstructure, constitutive properties, and the inherent flaw state. The integrated effect of these factors determines the mechanical strength and also modulation effects on the probe media used in NDE. For example, fiber fraction influences both mechanical strength and the attenuation of ultrasound. Therefore, by measuring ultrasonic attenuation, it is possible to predict variations in ultimate tensile strength due to fiber fraction variations, if other morphological factors remain constant.

The correlation procedure is rarely straightforward because more than one morphological factor will vary in any set of composite specimens. It is necessary, therefore, to consider a correlation cycle consisting of the following sequence of steps:

- (1) Specimen design and fabrication
- (2) Nondestructive evaluation
- (3) Destructive evaluation
- (4) Empirical/theoretical correlation

The last step leads cyclically to the first, as illustrated in Figure 1. The cycle ends only when the NDE step can reliably predict the results of the destructive step.

Step four examines the consequences of varying the constituents and processing procedures of step one. Step four also analyzes the results of steps two and three to establish

empirical correlations and to suggest theoretical foundations for the correlations.

Iterations of the cycle contribute to refinements in NDE methodology and specimen/composite design. Iterations should at least produce calibration curves from which mechanical strength properties may be predicted with known probability and confidence levels.

A number of investigators have demonstrated the feasibility of using NDE techniques to rank composites according to mechanical strength, for example, adhesive bond, tensile, and interlaminar shear strength, as shown in Figure 2. With few exceptions, only laboratory specimens were involved and the demonstrations stopped at step four of the correlation cycle. This limited success suggests the merits of the proposed approach. Further progress to complete the cycle on a laboratory scale is needed for verification before proceeding to the component stage.

5.2 ACOUSTO-ULTRASONIC CONCEPT

The previously described correlation cycle can, of course, be applied with a number of NDE techniques. Success depends on the degree of sensitivity to the modulation effects of the morphological factors governing the property being measured.

Acousto-ultrasonic techniques are particularly advantageous for mechanical property measurements. This is because the physical acoustic

properties in the ultrasonic regime are closely tied to mechanical properties through material morphology. For example, elastic moduli can be determined from ultrasonic velocity measurements while ultrasonic attenuation measurements of microvoid fractions correlate with interlaminar shear strength⁽¹⁰⁾.

It is particularly significant that acousto-ultrasonic NDE methods involve wave phenomena similar to stress waves generated during fracture. It has been shown that morphological factors that govern stress wave interactions during fracturing can be assessed via acousto-ultrasonic NDE methods⁽¹¹⁾. This suggests that acousto-ultrasonic NDE can form a basis for predicting the response to dynamic stresses as in impact and fracture.

The above concept has been demonstrated by acousto-ultrasonic measurement of a "stress wave factor." The stress wave factor is a measure of the efficiency of energy flow via stress wave propagation. The measurement can gage energy flow in the principal load directions. When applied to composite laminates, stress wave factor measurements provided an indirect measure of ultimate tensile strength. It was found that morphological features that reduced the stress wave factor also reduced ultimate tensile strength⁽¹²⁾. The principle involved is that in composites with brittle matrices, ultimate strength depends on effective distribution of stresses and

stress wave energy. Fiber reinforcement serves this requirement. Factors that impede prompt dissipation of stress energy contribute to sustaining local fracturing. Acousto-ultrasonic NDE methods give a quantitative measure of the efficiency of energy flow.

Morphological features that impede stress wave propagation include misaligned and broken fibers, microvoids, resin crazing, and similar flaws. Even where flaws cannot be individually resolved, their integrated effect on wave propagation and hence ultimate strength can be assessed acousto-ultrasonically. This answers the need for determining the integrated effect of defects in the evaluation of composite materials.

The acousto-ultrasonic concept given above is new and requires further experimental and theoretical development. Although feasibility has been demonstrated, application to diverse composite articles awaits the refinement and adaptation of methods and instrumentation.

5.3 DESIGN INTERACTION

The heterogeneous, anisotropic, and intrinsically anomalous nature of composite materials demands review and revision of nearly all disciplines involved in design, fabrication, and inspection. According to Reference 1, "the important structural characteristics, such as strength, stiffness, foreign object damage resistance,

environmental effects, and fatigue must be fully demonstrated for each new composite material system considered." Current and prospective NDE technology can meet the implied requirements only if it is an integral part of material development, testing, analysis, and component design and fabrication activities.

Naturally, the designer is concerned primarily with the various engineering factors that will guarantee the integrity of a structure. It is not always recognized that the inspectability of a structure is one of these factors. The appropriate approach would be to design all structures with inspectability as a major objective. This parallels the approach taken in materials testing that allows for instrumentation of test specimens. It is not farfetched to suggest that composite structures be equipped with "nervous systems" based on NDE techniques to monitor critical zones.

As a minimum, consideration should be given to factors that will enhance the NDE of critical structures. An example is the implanting of radio-opaque tracer fibers to improve the visibility of ply stacking and alignment in radiographs. In some cases, provisions for direct visual access may be sufficient. Ultrasonic inspectability can be enhanced simply by providing smooth surfaces to ensure good probe coupling. Metallic inserts in noncritical locations would aid in checking instrument calibration and sensitivity.

Measures for inspectability enhancement can be particularly important in cases where material property variations must be determined. Sophistication in the NDE techniques to be used should be matched by sophistication in the component design. Often minor adjustments in configuration, curvatures, smoothness, and like factors will suffice to ensure that superficial conditions do not affect the NDE.

It should not be assumed that inspection difficulties will always vanish by the use of innovative NDE methods. Advancements in technique precision and sensitivity may require design accommodations to be effective. The incentive to make the necessary accommodations is clear: advancements in NDE technology may be useless if reasonable provisions for their application are omitted in structural design.

6. CONCLUSIONS AND RECOMMENDATIONS

Nondestructive evaluation (NDE) should assure that defective materials are not put into service and that serviceable materials are not discarded. The current state-of-the-art in the NDE of composites is such that the serviceability of an article cannot be unequivocally decided on the basis of readily detectable defects. Because of a lack of realistic criteria, costly components containing only benign flaws may be scrapped while components with inadequate mechanical strength may be placed in service.

At present, understanding of the effects of defects is inadequate and requires further advances in experimental fracture mechanics of composites. Fiber composites often fail due to the existence of a subtle defect system that may be revealed only by advanced NDE techniques. The recommended approach includes development of NDE techniques that measure the integrated effect of microflaws and morphological anomalies on ultimate mechanical strength.

The preceding sections summarized the key issues pertaining to composites intended for strength-critical use in primary structures. NDE was highlighted as a vital link in the chain of supporting activities related to the reliability of composite structures. The interaction of principal activities is illustrated in Figure 3. Structural reliability and economical use of composites will require the close coordination of all the disciplines involved: Materials development, materials processing, engineering design, testing, failure analysis, and nondestructive evaluation.

Specific problems and approaches were cited relative to a new and more effective strategy for ensuring and assessing the reliability of composite structures. The strategy is based on the precept that although individual flaws may be important, the viability of a composite structure may depend on the integrated defect state. This calls for

NDE techniques that are sensitive to variations in microstructure, constitutive properties, and dispersed flaw populations that govern the ultimate mechanical performance of any particular article. Acousto-ultrasonic techniques are suggested as the "methods of choice" because the physical acoustic effects in the ultrasonic regime are closely tied to mechanical properties through material morphology.

Implementation of the above-described strategy will require:

- (1) Advanced computer augmented NDE instrumentation and data processing for materials characterization
- (2) Theoretical models explaining correlations between material morphology and NDE factors
- (3) Realistic accept-reject criteria and calibration standards consisting of representative composite materials
- (4) Incorporation of inspectability concepts into design to enhance NDE interpretation and quantification

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sonic Stress Wave Factor," Journal of Testing and Evaluation, JTEVA Vol. 7, No. 4, (1979), pp. 185-191.

8. BIOGRAPHIC SKETCH

The author is a materials research scientist specializing in nondestructive evaluation technology. His investigations have covered a wide range of NDE techniques for use on aerospace materials and structures. He is currently engaged in the study and development of ultrasonic technology for NDE of mechanical strength and related properties of advanced fiber composites, high strength metals, and ceramics.

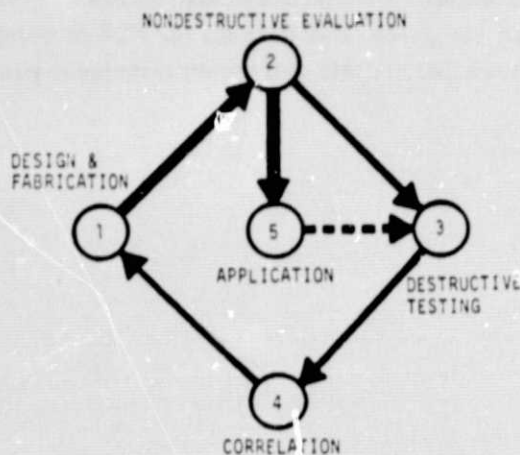


Figure 1. - Illustration of the correlation cycle. The 1-2-3-4 cycle can apply to laboratory specimens or actual composite components. Destructive evaluations are made on failed specimens or components to establish correlations between material performance and nondestructive evaluation results. The objective is the 1-2-5 sequence wherein nondestructive evaluations form the basis for reliability assurance during application of composites in service.

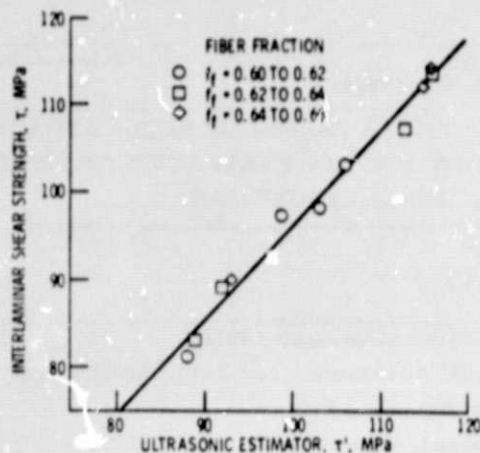


Figure 2. - Correlation of interlaminar shear strength and ultrasonic shear strength estimator. The above calibration curve was developed for graphite/polyimide fiber composite laminates. The ultrasonic shear strength estimator is based on stress wave attenuation and velocity measurements. The actual interlaminar shear strength was obtained by short beam shear destructive tests (from Ref. 10).

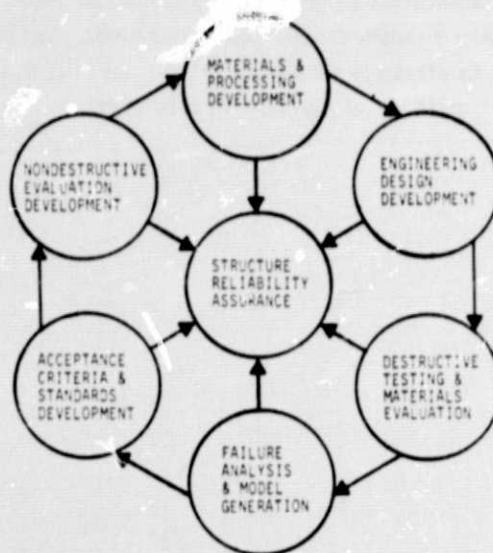


Figure 3. - Interaction of principal activities related to structural reliability assurance. The purpose of this diagram is to illustrate the strategic importance of each of the activities not only as they contribute to structural reliability assurance but also as they pertain to each other. The clockwise cycle indicates how each activity forms a link in the reliability assurance chain.